

Transport biofuels technological paradigm based conversion approaches towards a bio-electric energy framework

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ABSTRACT

The continuing dependence on fossil fuels and the rising energy use in the transport sector have resulted in increased research into viable transport biofuels to mitigate climate change and improve energy security. As transport biofuels now only have a small share of the transport sector energy supply and the complexity in providing the fuels because of issues related to available land and food security, this paper develops conversion path solutions for transport biofuel development based on a technological paradigm study. A data-driven approaches system (DAS) that combines visualization analyses with technological paradigm theory is proposed to reveal the key areas and trends in transport biofuels. Timeline, timezones, and cluster visualizations identified the transport biofuel technological paradigm (TBTP) from current transport biofuel developments; a pre-shift phase (including TBTP competition and TBTP diffusion) and a shift phase (TBTP shift), which respectively relate to conventional biofuels, advanced biofuels, and biofuel cells. However, from further DAS trend analyses and the practical findings, electric energy trends were revealed, indicating that there was a paradigm shift from the biofuel paradigm to a bio-electric energy paradigm. From the developed bio-electric energy framework, both indirect and direct methods were found to have led to an this electric energy conversion to an e-bio fuel cell vehicle for fuel cell electric vehicles (FCEV) and bioelectricity for electric vehicles (EV), both of which can contribute to a low-carbon, sustainable transportation future.

1. Introduction

As most of the increasing greenhouse gas emissions are coming from the transport sector, to ensure a shift to more efficient transport modes, it is necessary to substantially decarbonize the transport sector using renewable fuels [1,2]. Biomass is currently the most widely utilized renewable source for primary energy in many sectors, and biofuels, liquid and gaseous fuels derived from organic matter, can play an important role in reducing CO₂ emissions in the transport sector while enhancing energy security [3–6].

Biofuels provide only around 2% of transport fuel today; however, new technologies offer considerable potential for growth over the coming decades, with biofuels expected to account for 9% of all transportation energy consumption by 2030. This roadmap envisions that by 2050, 32 exajoules of biofuels are going to be used globally, providing 27% of the world's transport fuel [7]. As well as resulting in greenhouse gas reductions in the transport sector, biofuels can also

substantially contribute to energy security and socio-economic development [8]. Sustained policy support, high oil prices, and continued technological innovations will all lead to the rapid expansion of biofuels [9].

Biofuels are however, often criticized because of their effect on native ecologies, land competition with food production, and land-use problems (often first-generation biofuels) [10,11]. There are higher expectations for the second generation (advanced) biofuels which can be produced using different kinds of lignocellulosic materials, as well as from RES-based electricity and hydrogen [12,13].

To ensure biofuels can provide substantial GHG emissions reductions without harming food security, biodiversity, or the society, sound sustainability requirements are necessary [14,15]. Further, competition from electric vehicles or fuel-cell vehicles with high energy efficiency also needs to be considered. To cope with environmental transport problems and achieve sustainability and decarbonization, intensive research on transport biofuel development trends is required to identify

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efficiency improvements and further cost reductions along the production chain for different biofuels so as to ensure a stable, attractive, investment environment for biofuel commercialization.

Therefore, the research objectives in this paper are to discover the current developments in transport biofuels using a combination of theories and methods and to construct a systematic analytical framework. Further, as most previous research in related fields and even research in the electric energy conversion field has not focused on potential future trends, there is a need to explore transport biofuels conversion approaches so as to allow for an extension to other new transport biofuel paradigms.

To focus on transport biofuel developments, DAS was constructed based on bibliometrics and certain mining methods so as to conduct a comprehensive literature analysis, the key words from which could identify the focus trends in accordance with Kuhn's [16] paradigm theory. From technological paradigm theory (proposed by Dosi) [17] and the literature analysis, the existing transport biofuel paradigm was identified to describe the transport biofuel evolution and provide a method for the investigation of past trends as a prediction for future possibilities [18–22].

Thomas Kuhn's paradigm shift theory argues that paradigm shifts occur because the existing paradigm no longer fits the traditional framework. From the DAS and literature analysis, it was found that any electric energy conversion approach required the generation of a paradigm shift. The proposed bio-electric energy framework seeks to improve transport biofuel management rather than merely determine new technologies or sources; therefore, the approach taken in this paper is a marked improvement on other approaches and offers an entirely new perspective.

The remainder of this paper is structured as follows. The DAS and mining trends are presented in Section 2, which combines paradigm theory and a Citespace mining tool based on bibliometrics to determine current transport biofuel developments. Section 3 gives the data mining results to highlight the existing biofuel paradigm, and current transport biofuels trends. The results and discussion are given in Section 4, in which we give a keyword analysis of the theoretical paradigmatic framework, propose an emerging electric energy paradigm as the new paradigm shift, and highlight the bio-electric energy framework for the coming paradigm shift. Conclusions are given in Section 5.

2. Methodology

In the alternative fuels transport research community, there have been few bibliometric studies. Therefore, in this paper, a complete scientific mapping analysis of image-based visualization study is presented, in which the transport biofuel research field from 1990 to 2017 was analyzed and the conceptual evolution revealed. The data set was completed from the selection of documents that contained the keyword “transport biofuels”. The science mapping analysis was performed using the software tool, CiteSpace [23,24].

Massive data creates an unprecedented opportunity for researchers to leverage increasingly mature visualization techniques to address current transportation needs while bringing greater clarity to emerging transportation problems. The most promising data visualization applications can promote cooperative research, knowledge-sharing, and information discovery [25]. Visual analytics research in recent years has increasingly focused on the development of a particular family of methods such as image-based visualizations [26], which has resulted in an increase in the bibliometric analysis of intelligent transportation system research based on scientific mapping and visual analysis [27,28].

2.1. Paradigm and scientific mapping

Science mapping analysis is a powerful bibliometric technique for the study of the conceptual structure of a particular research field

[29,30], as it allows for the monitoring of a scientific field and a delimiting of the research areas to determine structure and evolution. Based on domain knowledge, the scientific knowledge atlas gives an image of the scientific knowledge development process and structure and shows the complex relationships between the knowledge units or knowledge groups, the network structure and interactions as well as the overall evolution. As the CiteSpace information visualization tool can identify the distinctive features of the spectrum, it has been widely used. One of the main theories informing the use of CiteSpace for scientific knowledge mapping was Kuhn's scientific development theory, which can be evidenced in the CiteSpace prediction function and can predict the status of a field in the future.

Kuhn saw scientific development as the historical scientific revolutionary process. In the pre-scientific period, science did not develop as a unified paradigm. However, as science developed through continual problem solving in the scientific community, there was a need for a new paradigm which resulted in a scientific revolution; after entering the new paradigm, this became the new normal. Therefore, using CiteSpace along with the scientific development model, the formation of a knowledge map built from science citation clustering accumulation, diffusion, and transformation reveals frontier research fields and identifies the knowledge emergence and evolutionary processes.

CiteSpace, a free Java application for visualizing and analyzing citations and the content of scientific literature, was used as the main analysis tool to detect and visualize the emerging trends [31]. Using co-citation network analysis, CiteSpace can identify the co-citation clusters in a literature index and trace the research trends. The main CiteSpace software techniques are spectral clustering and feature selection algorithms that allow for a visualization of the results to make sense of the trends and evolutions [32].

2.2. Data-driven approaches

The CiteSpace data is based on extracted text data (such as keywords) from the Web of Science database, after which data clustering and other forms of visual mapping can be performed [33]. As CiteSpace can extract more keywords and provide more detailed analyses, our exploration of “transport biofuels” used this method for data retrieval and visual analysis.

To determine the relevant research foci for “transport biofuels”, data-driven approaches using popular academic search engines was conducted, after which appropriate technology and software based on data flow were used to evaluate the relevant research papers [34]. Combined with science mapping (theory) and Citespace (tool), the development of the DAS and the research process were described, and the visualization results given. The organization of the Data-driven Approaches System (DAS) is shown in Fig. 1, in which it can be seen that three main module approach was taken; Data Collection (a) and Data Analysis (b), with Visualization (c) being the results from CiteSpace, the visual interpretation for which involves auto-labeling, graphic effects, and graphic interpretation as the key steps. The results obtained from the visualization module allowed for the trajectories and current transport biofuels paradigm to be identified, with the complete DAS process being a dynamic cycle.

The Data Collection module collects the most relevant records from the appropriate citation index databases. In this paper, the Web of Science (WoS) was chosen as the primary database as it accesses multiple databases and covers the longest publication years. Search query design is an iterative activity. In this step by applying Boolean operators and Web of Science standard field tags, the Web of Science database is explored. To ensure the bibliographic references and research topics were highly relevant, a variety of search strings were tried. The final search strings were (Xi OR Yi) using topic retrieval [35], for which Xi represented keywords that referred to ‘transport* biofuel*’, Yi represented ‘vehicle biofuel*’ (also shown in Fig. 1). 3908 papers were identified, which were then refined by literature type: ARTICLE,

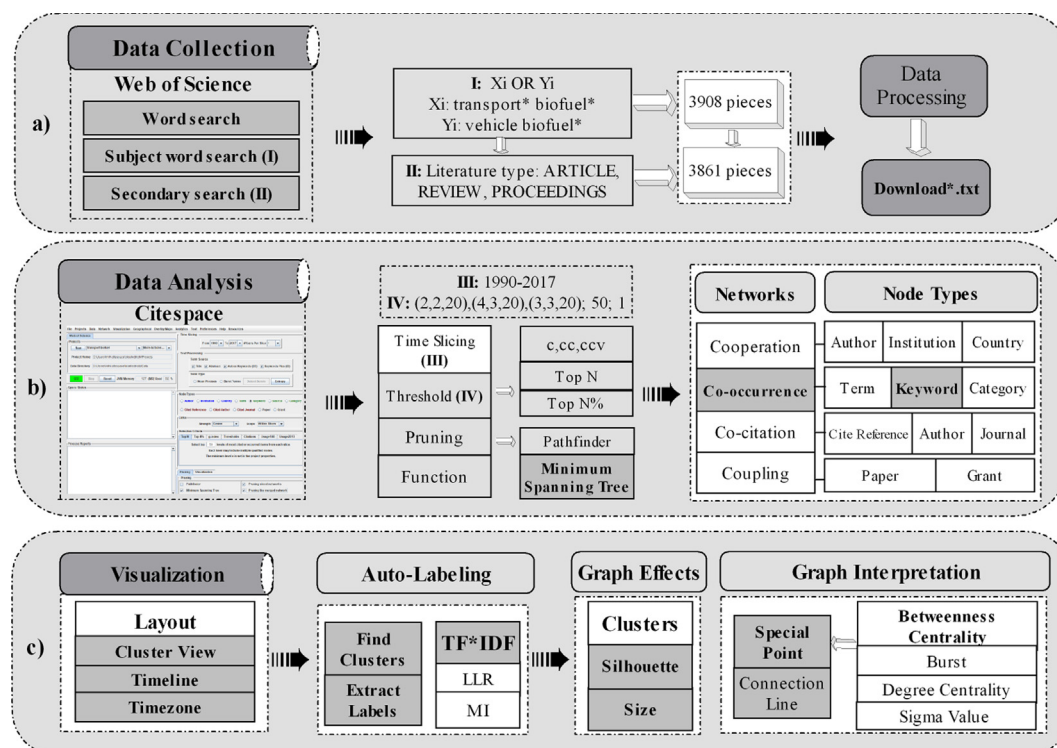


Fig. 1. DAS Literature mining.

REVIEW, PROCEEDINGS, after which 3861 results were exported in a text format file for the CiteSpace input file.

The data were processed (Data Analysis) using CiteSpace with the time slice ranging from 1990 to 2017 (the initial year for the research was 1990), the networks constructed using the 'Minimum Spanning Tree' as the pruning method, and keywords were chosen for the node types to clearly identify the range within specified boundaries to provide more objective definitions. As a type of co-occurrence analysis, keyword-based analysis has played an important role in understanding knowledge development dynamics [36]. In the Visualization module, different network analysis views; cluster, timeline, and timezone; were available, from which the patterns and trends in transport biofuels literature were revealed.

2.3. Data clustering and visualization analysis

A visualization of the search results to make sense of the trends and evolutions is the main characteristic of CiteSpace [32], with the CiteSpace cluster analyses revealing the relationships between the keywords from the related articles. The 'Cluster View' graph is shown in Fig. 2.

The modularity and mean silhouette scores are the two important metrics used to describe the overall structural network properties. In general, the modularity values in Fig. 2 (0.9127) were relatively high, which indicated that the network's loosely coupled clusters were reasonably divided. The silhouette measure is used to determine whether the data is appropriately clustered; when the silhouette measure is close to one, the data is appropriately clustered and when it is close to minus one, the data is not appropriately clustered. However, when the silhouette measure is near zero, the data is on the border of these two natural clusters [37]. The mean silhouette scores suggested that on average, the cluster homogeneity of transport biofuel trends (0.4224) was relatively high.

From the auto-labeling, 38 clusters were found; therefore, to determine the most appropriate clusters, silhouette and size measures were used. Three clusters with the cluster label (TF*IDF); 'biomass fuel',

'lignocellulosic feedstock' and 'biofuel cell'; were extracted as they had high silhouettes (ID: 10, 11, 15; silhouette: 0.526, 0.615, 0.706) and were a large size (19, 19, 17). As the keywords in the above three clusters were distinct, it was decided that these were representative of the different transport biofuels. All three clusters and the associated keywords were gathered into three groups; Group I, Group II, and Group III; as shown in Fig. 2, and listed in Table 1 (In Table 1, the number in front of the keywords indicates word frequency).

Changing the layout to 'Timeline View' and 'Timezone View' in Fig. 3, it can be seen that the clusters vary with time (year), with the distribution of the three groups each occurring in different time periods; 'biomass fuel', followed by 'lignocellulosic feedstock' and then 'biofuel cells', clearly indicating the transport biofuel evolution. Other information was also retrieved from the other clusters, such as 'biomass-burning emissions' from 'ID1: (15.23)', 'concerning biofuel' from 'ID7: (7.81)', and 'future emissions' from 'ID9: (10.15)', each of which were extracted to represent transport biofuels problems. Therefore, from this initial analysis, three clear transport biofuel stages were revealed.

2.4. Electric energy trends discovery

Fig. 4 shows the timezone view for the development trends derived from the keywords 'fuel' to 'electric'. In this figure, the black font on the top of the nodes represents the cluster label, and the lower blue and red fonts represent the keywords; blue for 'fuel' and red for 'electric' and 'fuel cell'. The number in front of the keywords is the frequency, with the size of the number being proportional to the keyword frequency.

At the beginning of the timeline, there are many 'fuel' class keywords; for example, 'fuel'(149), 'fuels'(97), 'fuels alternative'(36), 'liquid biofuels'(18), and 'liquid fuels'(17); and the 'fuel' keywords are also distributed towards the end of the timeline but with few number, like 'fuel ethanol'(36). The related 'electric' keywords distributed at the beginning are 'fuel-cells'(18); however, most of the distribution is toward the end of the timeline such as 'biofuel cells'(120), 'electrodes'(26), 'electron-transport'(18), 'microbial fuel-cells'(18), and 'electrode'(16).

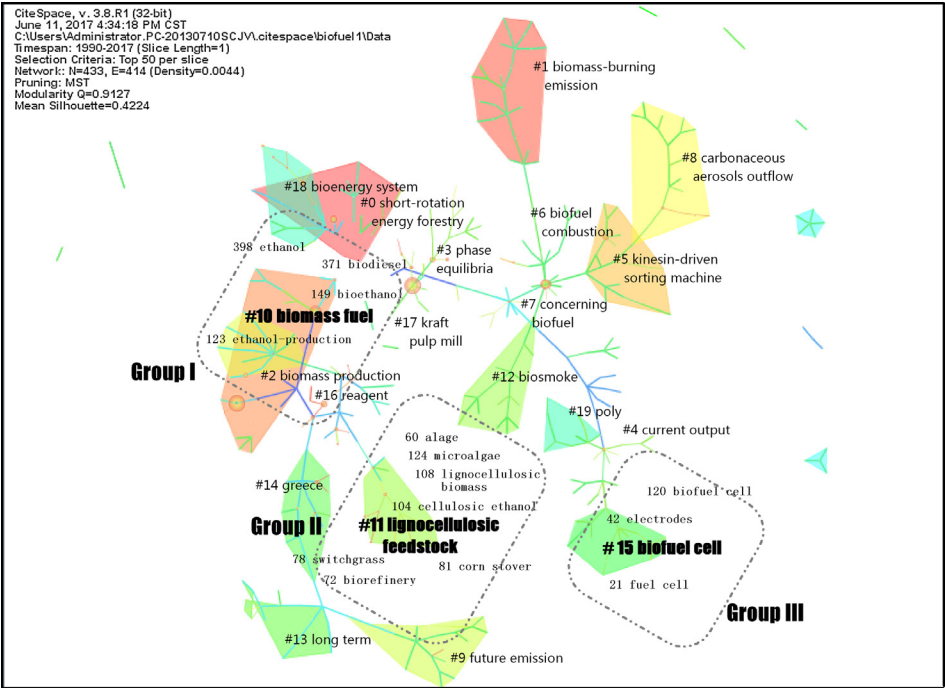


Fig. 2. Keyword focus trend analyses (Layout: Cluster View).

3. Currents trends for transport biofuels

Biofuels are commonly divided into first, second, and third generation biofuels [38]; however, the same fuel may be classified differently depending on technological maturity, GHG emissions balance, or the feedstock used. As there were no obvious existing transport biofuel trends emerging from the visual knowledge map, there were three distinct clusters; ‘biomass fuel’, ‘lignocellulosic feedstock’ and ‘biofuel cells’; which could be further distinguished as conventional or advanced [39]. Therefore, these three development stages were labelled ‘conventional biofuels’, ‘advanced biofuels’ and ‘biofuel cells’. By combining the three life cycle stages of the technological paradigm theory and the above three cluster classifications, the transport biofuel technological paradigm framework (TBTP) was built, as shown in Fig. 5. These three stage cluster items can be classified under this framework into a competition stage, a diffusion stage, which are pre-shift phases and cover biofuel feedstock, and a shift stage focused on biofuel cells.

3.1. Biofuels in the pre-shift phase

Global energy and environmental problems have stimulated biofuel transportation development efforts. The literature mining and transport biofuel technological paradigm framework (TBTP) indicated that conventional biofuels and advanced biofuels were representative of the pre-shift phase (including the TBTP competition and diffusion phase). The commercial processes for these two biofuels were analyzed and are shown in the left hand table in Fig. 5 [40,7].

(1) Conventional biofuels

From the focused trend analysis and the paradigmatic evolution theory combination, conventional biofuels, which have been the main biofuels in the transportation sector [41]. Conventional biofuels, commonly referred to as first-generation, include sugar- and starch-based ethanol, oil-crop based biodiesel, straight vegetable oil, and anaerobic digestion derived biogas [7,42]. Conventional biofuel technologies, or first generation biofuels such as sugar and starch-based ethanol, conventional biodiesel, and biogas have well-established processes for producing commercial scale biofuels. The production costs from sugar and starch, however, have proven to be very sensitive to feedstock prices, which have been very volatile in recent years. However, efficiency could be improved and costs lowered by using more effective amylase enzymes, decreasing ethanol concentration costs, and an enhanced use of co-products. Biodiesel is produced from raw vegetable oils derived from soybean, canola, palm oil, or sunflowers, as well as from animal fats and used cooking oil. These oils and fats are then converted to biodiesel using methanol or ethanol. The profitability of conventional biodiesel production, therefore, is also sensitive to feedstock prices. Biogas is often used to generate heat and electricity, but can also be upgraded to biomethane by removing the CO₂ and hydrogen sulfide (H₂S) and injecting it into the natural gas grid. Biomethane can also be used as fuel in natural gas vehicles.

(2) Advanced biofuels

Due to increased market demand and industrial competition, the TBTP diffusion stage is emerging gradually based on technological paradigmatic evolutionary theory. With a transition from conventional to newer technologies, advanced biofuels were the dominant

Table 1
A review of selected clusters and relevant keywords.

Cluster ID	Size	Silhouette	mean (Year)	Label (TF*DF)	Keywords in cluster
10	19	0.526	1992	(9.25) biomass fuel	398 ethanol; 371 biodiesel; 149 bioethanol; 123 ethanol production
11	19	0.615	1999	(11) lignocellulosic feedstock	124 microalgae; 108 lignocellulosic biomass; 104 cellulosic ethanol; 81 corn stover; 78 switchgrass; 72 biorefinery; 60 algae
15	17	0.706	2007	(7.89) biofuel cell	120 biofuel cell; 42 electrodes; 21 fuel cell

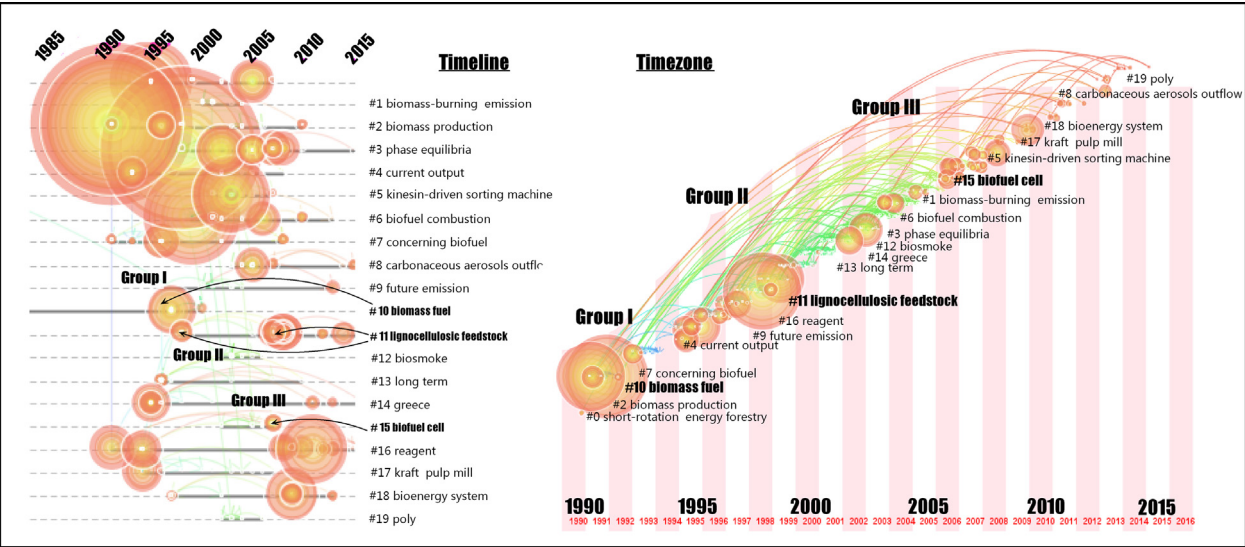


Fig. 3. Keyword focus trend analyses (Layout: Timeline and Timezone).

designs in the TBTP diffusion stage. Advanced biofuels are commonly referred to as second or third-generation fuels and include hydro-treated vegetable oil (HVO) based on animal fats and plant oils, as well as biofuels based on lignocellulosic biomass such as cellulosic-ethanol, biomass- to-liquids (BtL)-diesel, and bio-synthetic gas (bio-SG) [43,44]. Compared to traditional biofuels such as ethanol, advanced biofuels have significant advantages, such as higher energy density, lower hygroscopicity, lower vapor pressure, and are compatible with existing transportation infrastructure [45]. Advanced biofuels have developed rapidly over the past few years. Although further production improvements are necessary, advanced biofuels offer significant advantages over traditional biofuels. However, to be economically feasible, the yield, titer, and productivity need further improvements. There has been increased research interest in these types of biofuels in recent years; generally, however, even though advanced biofuel technologies are conversion technologies, most are still in the research and development (R&D), pilot, or demonstration phases.

Cellulosic ethanol. Bioethanol can be produced from ligno-cellulosic feedstocks through a biochemical conversion of the cellulose and hemicellulose components of biomass feedstocks into fermentable sugars [46]. The sugars are then fermented to ethanol, following the same conversion steps as conventional biofuels. Cellulosic ethanol has the potential to perform better in terms of energy balance, GHG emissions and land-use requirements than starch-based biofuels [46]. The first large-scale plants for this technology are now starting to be developed for production.

Advanced biodiesel. These fuels are expected to be blended with fossil fuels in any proportion, can use the same infrastructure, and should be fully compatible with heavy duty vehicle engines. Advanced biodiesel and bio-kerosene are expected to become increasingly important to reach sustainable transportation targets as the demand for low-carbon fuels with high energy density is expected to increase significantly over the long term. Advanced biodiesel includes hydro-treated vegetable oil (HVO) and biomass-to-liquid (BtL) diesel.

Bio-synthetic gas. Bio-SG is biomethane derived from biomass using thermal processes. The first demonstration plant to

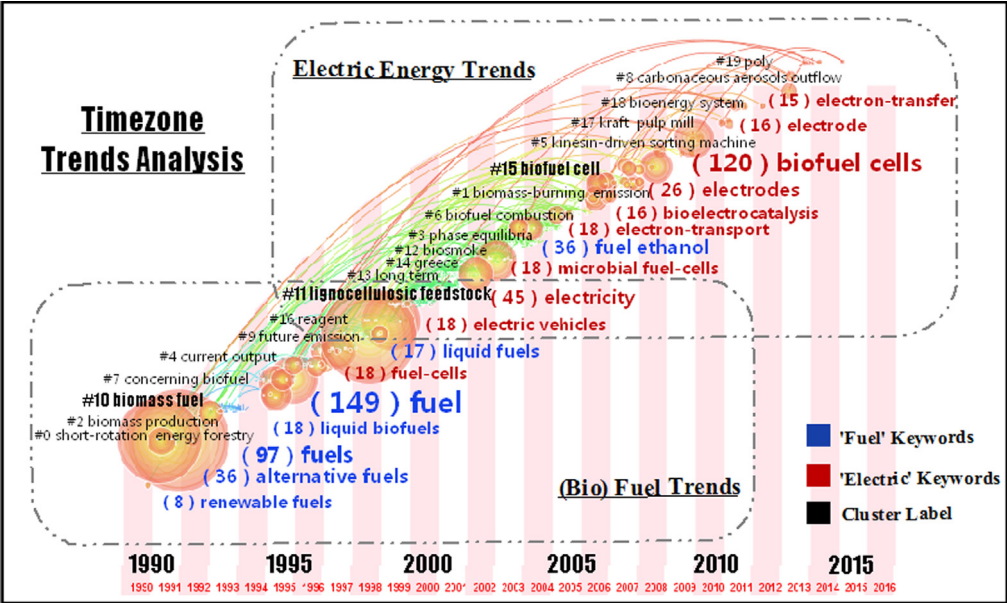


Fig. 4. DAS Trend analysis.

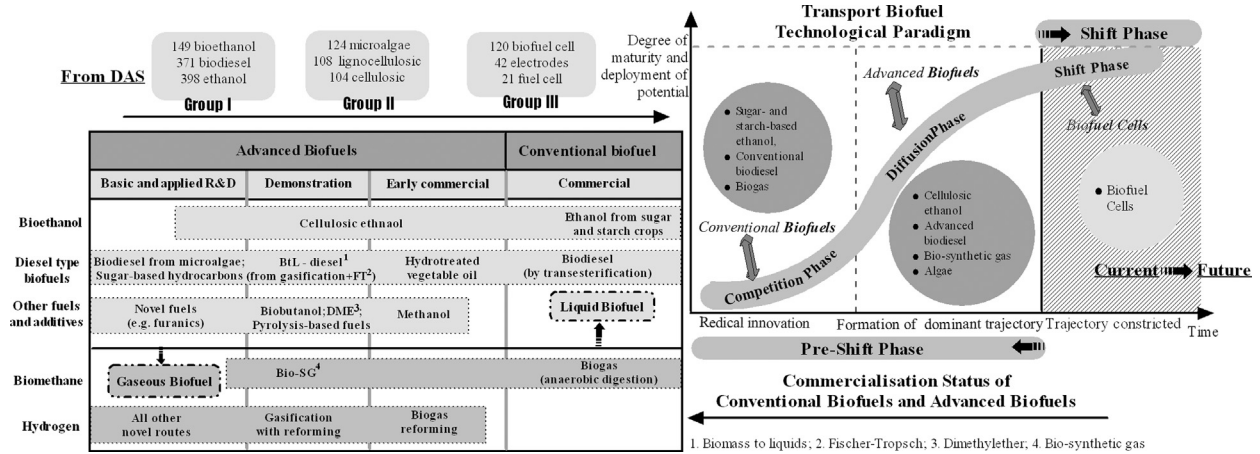


Fig. 5. Pre-shift stage and TBTP evolution based on the technological paradigm.

thermochemically produce biomethane out of solid biomass started operations in late 2008 in Gssing, Austria, and another plant has been planned in Gothenburg, Sweden [47]. The deployment of natural gas vehicles (NGV) that can also run on biomethane derived from anaerobic digestion or biomass gasification has started to grow rapidly.

Algae. Algae has been cultivated commercially since the 1950s mainly for the pharmaceutical industry; however, it has only recently received attention as a potential biomass source. Algae promises a potentially high productivity per hectare, can be grown on non-arable land, can be grown in a wide variety of water sources (fresh, brackish, saline, and wastewater), and can potentially recycle CO₂ and other nutrient waste streams [48]. However, algae cultivation faces several challenges related to the availability of locations with sufficient sunshine and water and the required nutrient inputs, and the development of efficient oil extraction methods [48,44].

First and second generation biofuels are among the few low-carbon alternatives for road transport that are currently commercially available or are in an early commercialization phase. However, there is still a long way to go, and the current emerging research focus is biofuel cells in the shift stage, which is what this paper is specifically focused on. There are still problems with transport biofuels related to land competition and food security. However, at present, transport biofuel cells are by and large still in the research stage. As a result, the future of transport biofuels is unknown; however, there are some upcoming innovations in the TBTP shift stage.

3.2. Biofuel cells for the shift phase

The emergence of disruptive technologies [49] and technological limitations [50] which has been accompanied by full competition and market demand, has moved the technological paradigm into the shift phase. From our focused trend analyses, biofuel cells have been identified as one of the more promising technologies for future clean energy [51,52] that could be developed in the TBTP shift phase. Fuel cells convert the energy chemically stored in a fuel, such as hydrogen, into an electrical energy output through electrochemical reactions [53]. Fuel cell operations are efficient, clean, and silent and can be applied to large-scale stationary systems for distributed power generation as well as to small-scale portable power supply devices for micro-electronic equipment and auxiliary power units (APU) in vehicles [54].

The utilization of biofuel cells using carbohydrates as the power source would not only offer environmentally friendly benefits, but would also remove the fire and accident risks associated with transporting large amounts of volatile, flammable fuels. There are several classes of biofuel cells, with the most recent advances converting chemical fuels to electrical power using catalytic enzymes [55,56], an innovation that is expected to be a next-generation energy device because of the possibilities of higher energy density and improved safety. A mediated electron-transfer (MET) type biofuel cell system has also been developed, in which electron transfer mediators shuttle electrons between electrodes and enzymes [57]. The reaction scheme for the biofuel

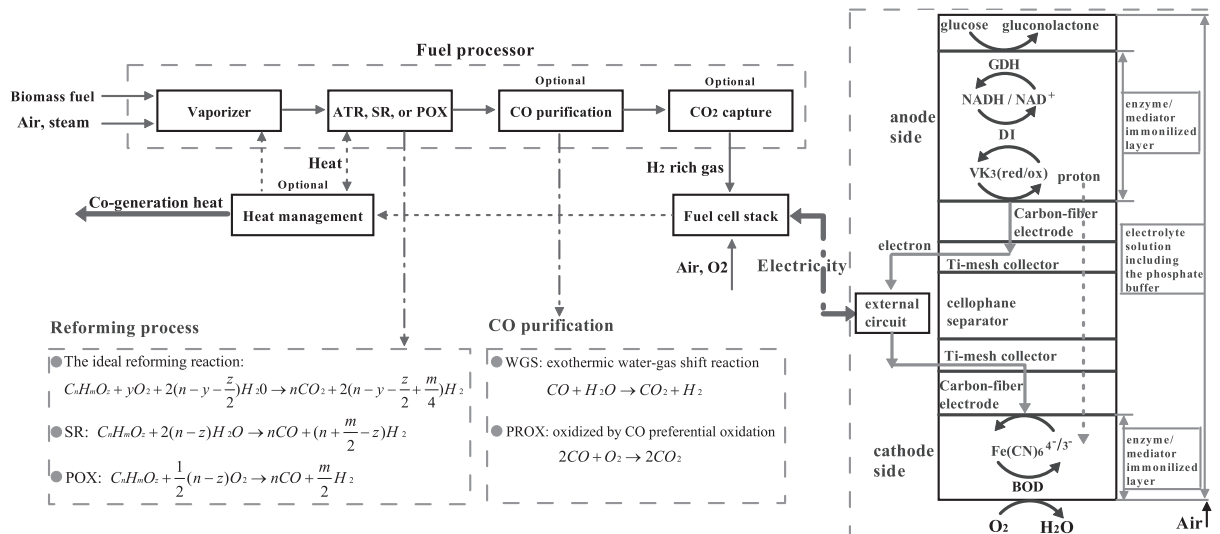


Fig. 6. Fuel processor and reaction scheme for biofuel cells.

cells is shown on the right in Fig. 6. This system has the advantage of enhancing current density when the mediator concentration is sufficiently high compared to direct electron-transfer (DET) type systems or systems using microorganisms.

Fuel cells coupled with biomass-derived fuel processors could be considered one of the most promising energy supply systems in the future. These fuel cells have the ability to convert renewable energy into an environmentally friendly CO₂ neutral energy source [58,59]. Biomass-derived fuels, such as ethanol, methanol, biodiesel, glycerol, and biogas, are fed into a fuel processor as raw fuel, which is then reformed through autothermal reforming, steam reforming, partial oxidation, or other reforming methods [60]. In a fuel processing system, the most important element is the fuel reformer, which converts the fuels into a hydrogen rich gas. A vaporizer is required to preheat the fuels, steam, and air before they are fed into the reformer. After the reforming process, CO purification and CO₂ capture is possible, after which the purified H₂ rich gas is fed into the fuel cell to generate electricity. Higher system efficiency can be achieved using combined heat and power generation systems (CHP), with the overall system fuel utilization exceeding 90% [61]. The “fuel processor-fuel cell CHP system” allows for a better control of the mass and thermal conversions as it has a superior thermal balance (left side of Fig. 6).

As the development of biofuel cells for practical applications is still in its infancy, significant market penetration is expected to take a long time as there is significant potential for further improvements. Most current methods only partially meet the specified requirements for fuel cell applications in terms of output energy density, hydrogen yield, product gas purity, start-up times, emissions, as well as equipment size and weight, especially for portable and on-board applications [55]. It is important to understand the past and ongoing technological developments to further develop practical biofuel cell systems.

4. Results and discussion

Transport is a major source of unsustainable energy use because of its near complete dependence on liquid fossil fuels. At present, the transport sector accounts for 27% of global final energy consumption and this is expected to increase to 50% by 2035 [62]. Because of its 94% reliance on oil, transport is the second largest source of CO₂ emissions at 6.3 Gt or 24% of the total, compared with power generation (40%), industry (16%), buildings (12%) and agriculture and non-energy use [63,62]. Ever-growing energy needs and depleting fossil-fuel resources demand the pursuit of sustainable energy alternatives, including both renewable energy sources and sustainable alternative fuels for the transport industry [64,65]. For transport biofuels, there are still major production concerns in terms of sustainability and the displacement of food production, particularly as large quantities of biofuels would be necessary to decarbonize long-haul road freight, aviation, and shipping.

4.1. Current vehicle barriers

Transport today is dominated by oil-derived fuels and internal combustion engines, making it both economically and environmentally unsustainable. Vehicle combustion engines account for more than one-fifth of the world's carbon dioxide emissions, making them a significant contributor to global climate change [66]; therefore, these need to be replaced with low-carbon, renewable fuels and alternative low-emission, high-efficiency vehicles [67–69]. The main technological options currently being considered are focused primarily on FCEV and EV [70]. FCEV have the possibility of providing transport utility comparable to today's vehicles while at the same time meeting climate and energy security targets [71]. Further, developments in battery technology have advanced electric vehicles as potentially important for the decarbonization of transport [72,73].

Fig. 7 compares conventional gasoline vehicles (ICE) to battery

electric vehicles (BEV) and hydrogen fuel cell electric vehicles (FCEV) from the perspective of performance, environmental effect, economics, power sources, and existing infrastructure. Combined with the analysis above, biofuel substitution for these three vehicle kinds is presented. As biofuels are oxygenates (e.g. ethanol), they can help reduce combustion emissions compared with ICE. Alternative energy sources for hydrogen fuel cell electric vehicles and battery electric vehicles and the barriers are further discussed in the following.

(1) Hydrogen production for FCEV

FCEV are electric vehicles that use hydrogen stored in a pressurized tank and a fuel cell for on-board power generation [74]. FCEV can provide the same performance as conventional cars at much lower carbon emissions. However, the US Secretary of Energy Chu outlined four primary barriers to such a hydrogen initiative [75]. Car manufacturers still need a fuel cell that is sturdy, durable, and cheap, as well as methodologies that allow for the storage of enough hydrogen on board for long-distance travel [76]. A new hydrogen distribution infrastructure would also be needed and even then, the greenhouse-gas benefits gained would be marginal until a cost-effective method is found to convert hydrogen from low-carbon energy sources rather than from natural gas [77].

From a climate perspective, the main question facing hydrogen is the gas source [74]. At present, the cheapest source is derived from a chemical reaction between steam and natural gas; however, as this process produces carbon dioxide, the total greenhouse-gas production for a fuel-cell vehicle is only a little less than for a conventional petrol vehicle [72,74]. The challenge, therefore, is to extract hydrogen from carbon-free renewable sources.

Hydrogen refueling stations can be supplied from two alternative technologies; hydrogen can be produced at refueling stations using smaller-scale electrolyzers or natural gas steam methane reformers, or can be transported from a centralized production plant [78]. Each approach has its own advantages and trade-offs. As biofuel and battery powered electric vehicles offered quicker and cheaper routes to low carbon transportation, interest in hydrogen fuel-cell vehicles has somewhat faded, which can be an indirect way to realize biofuel's application in transportation sector by converting biofuel to hydrogen as power source for FCEV. Of course, the next step is biofuel cell's direct application in vehicle.

(2) Power supply for EV

Electric vehicles (EV) have recently gained increasing worldwide interest as a promising long-term solution to sustainable personal mobility [79,80]. EVs are powered by electric motors and therefore have reduced emissions, and improved efficiency [81] as well as digital controls that allow for diverse energy sources. Improvements in battery technology are expected to enable longer driving ranges to be achieved at lower costs, increasing the cost-competitiveness of EVs and lowering the barriers to adoption [73].

However, electric cars are not really zero emissions vehicles as they just shift the pollution away from the car to where the power is being produced, with most being powered by burning coal, which is dirtier and more environmentally destructive than burning gasoline [82]. While it is true that electric cars are powered by electricity, in most countries, the regular charging is taken from the local electricity network, which is generated from burning coal. Therefore, the power plants that are providing the energy are not emissions-free; even in California, 60% of electricity came from burning fossil fuels in 2015, while solar and wind generation together made up less than 14% [83].

Therefore, while electric cars eliminate the need for oil/petrol transportation, the value depends on the electricity source. Low and zero emissions can only be achieved when most electricity is coming from a mix of low-carbon sources such as solar, wind, or nuclear. However, burning biomass to produce electricity could be a new alternative power supply source for electric vehicles EV,

	Conventional Gasoline Vehicle (ICE)	Battery Electric Vehicle (BEV)	Fuel Cell Electric Vehicle (FCEV)
Power Source	Internal combustion engine Gasoline	Rechargeable battery Electricity	Hydrogen fuel cell Hydrogen
Existing Infrastructure	Widespread/ubiquitous	Limited, but extensive near-term (before 2020) expansion	Very limited with targeted near-term (before 2020) expansion
Performance	* Highest driving range * Best top speed and refueling time * Only service intervals shorter	* Limited energy storage capacity and driving range * Refueling time in order of hours * Ideally suited to smaller cars and urban driving	* Similar range to ICE * ~600 km average driving range * Refueling only takes a couple of minutes * Fewer service needed
Environment	* Highest CO₂ and local vehicle emissions * Unlikely to meet EU CO₂ reduction goal for 2050	* High CO₂ reduction (~80%) if CCS or renewable energy is used * Depends on electricity footprint * No local vehicle emissions	* High CO₂ reduction (~80%) compared to today with CCS & water electrolysis * No local vehicle emissions * Lowest carbon solution for large car
Economics	* Most economic vehicle * Lowest purchase price * Higher fuel or maintenance cost * Existing infrastructure	* Economic for smaller cars * Purchase price higher than ICE * TCO higher than ICE TCO * Fuel costs comparable to ICE	* Purchase price is higher than ICE * TCO comparable to ICE for larger cars, not smaller cars * Infrastructure cost comparable cost to BEVs
Biofuel	Source Alternative: Biofuel Low CO ₂ if 100% biofuels	Source Alternative: Bioelectricity Biomass → Bioelectricity	Source Alternative: Hydrogen' Biofuel → Hydrogen'

Excellent
 Good
 Moderate
 Challenged

Fig. 7. Comparative analysis of ICE, BEV and FCEV.

which is the direct way to realize the bioelectricity's application in transportation sector.

4.2. Emerging electric energy paradigm

The keyword foci and trend analyses (Fig. 4) show that the transport biofuel trends are towards the use of fuels for electric energy. In combination with the technological paradigm theory, there is also information about 'electric' and 'fuel cell' in the shift stage, pointing to an electrical energy paradigm trend in the future; thus indicating that there is expected to be a paradigm shift from the fuel paradigm to an electric energy paradigm.

Biomass can power either an internal combustion engine or electric vehicles. After the analysis of the potential electric energy trends, in this section a description is given of the practical potential of biofuel fuel cells first as an indirect way and technological developments towards better bioelectricity sources as a direct way. From this analysis, there is a new trend emerging for the use of biofuels for electrical energy rather than for the direct use of fuels, for which there are both indirect and direct methodological contributions.

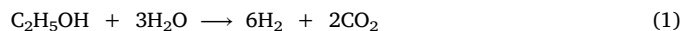
4.2.1. Indirect biofuel cell promotion

The current application of fuel cells in the transportation field has mainly been for fuel cell electric vehicles (FCEVs) powered by hydrogen. FCEVs and hydrogen fuel infrastructure are still in an early deployment stage, and biofuel cell development for practical applications is only in the very early stages, with applications for transportation not yet developed. An indirect application, however, has been the development of the e-Bio Fuel Cell (Fig. 8) by the Nissan Motor Co., Ltd., which overcomes the common hurdle to the deployment of traditional hydrogen fuel cell vehicles - the lack of hydrogen fueling infrastructure.

The e-Bio Fuel Cell is a Solid Oxide Fuel-Cell (SOFC)-powered system using bio-ethanol as the on-board hydrogen source [84]. This new e-Bio Fuel Cell system, a world-first, features an SOFC stack [85,60] and an on-board reformer to convert 100% ethanol or ethanol-blended water (55% water, 45% ethanol) to hydrogen. The e-Bio Fuel Cell system can be run 24 * 7, features a quiet drive and short refueling

time, is versatile, has an ample power supply to support refrigerated delivery services, and is expected to have running costs equivalent to that of EVs when using ethanol-water blends.

Nissan's e-Bio Fuel Cell system produces hydrogen from ethanol or ethanol-water blends through the on-board reformer. Its working principle is shown in Fig. 9. The main reaction for this is:



The solid oxide fuel then generates electricity through a reaction of hydrogen with oxygen from the air. The oxygen ions move through the fuel cell's electrolyte, generating power [86,87]. A benefit of the high operating temperature is that a highly active catalyst is not necessary; therefore, no rare metals are needed. The system reuses the heat generated by the reaction for the reformer.

When power is generated in an SOFC system, CO₂ is usually emitted. With a bioethanol system, the CO₂ emissions can be neutralized in the feedstock and/or production process, allowing it to have a Carbon-Neutral Cycle, with nearly no CO₂ increases. Nissan said that in the future, the e-Bio Fuel-Cell will become even more user friendly. Ethanol-blended water is easier and safer to handle than most other fuels. As this will remove limits on creating a totally new infrastructure, it has great potential for market growth. Therefore, the e-Bio Fuel Cell may be a key step in the middle stages to realize the final goal of biofuel cell applications for the transportation sector and entry into the emerging electric energy paradigm.

4.2.2. Direct preferred bioelectricity

Given the limited area of land available to grow biofuel crops without causing direct or indirect land-use impacts [88,89], bioenergy applications should maximize the efficiency of a given land area to meet both transportation and climate change goals. In one study, the use of willow biomass for electricity was shown to have greater transportation fuel displacement and GHG offsets than corn ethanol [90], so this could be a direct way to realize bioelectricity for the transportation sector.

Researchers led by Campbell of the University of California modelled the entire system from crop cultivation to vehicle propulsion and compared cumulative greenhouse-gas emissions for both biofuels and bioelectricity. It was found that bioelectricity outperformed ethanol

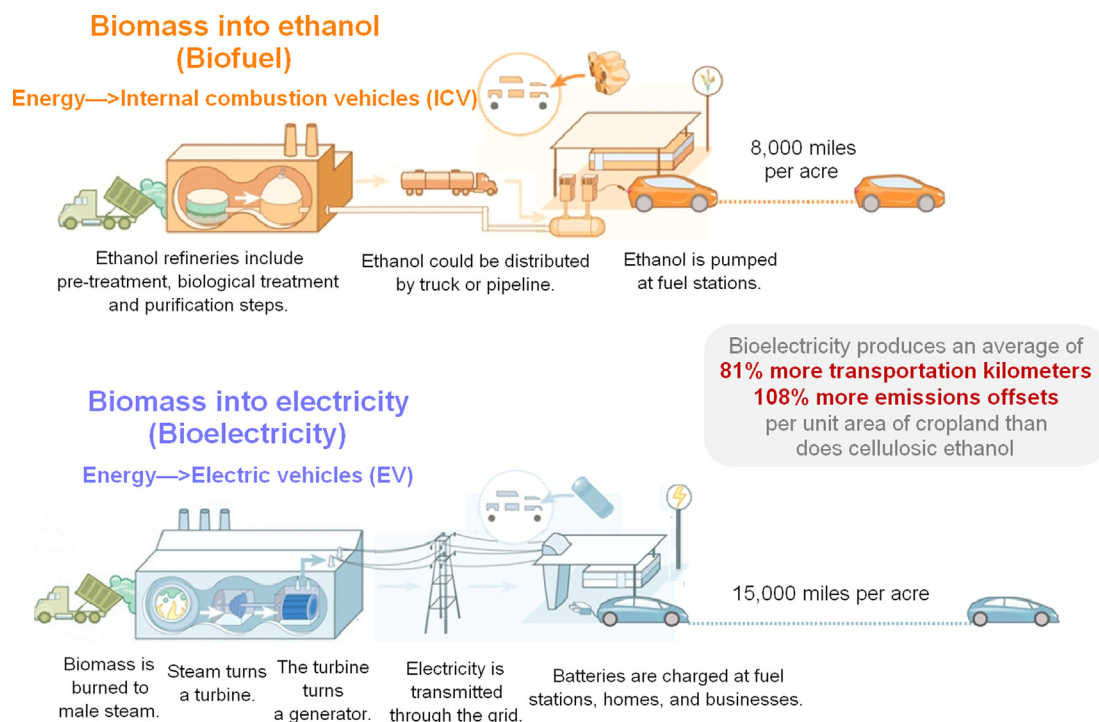


Fig. 10. Transportation and GHG offsets from bioelectricity and ethanol.

4.3. Sustainable paradigmatic structure

As a core component for socioeconomic system interactions and development, transportation sustainability has become an increasing research interest because of the linkages between environmental protection, economic efficiency, and social progress. Therefore, vehicles such as EV and FECV are viable transport alternatives for the implementation of new engine and new energy sustainability improvements. Fuels can also be improved through the use of alternatives such as biofuels, electricity, or hydrogen. In this paper, through the examination of transport biofuels and the above analysis, a sustainable transport paradigmatic structure within a dynamic framework was developed from an energy, environmental, and conversion perspective, as shown in Fig. 11.

Energy Security. Fuels based on renewable energy sources (RES) such as biofuels and electricity and hydrogen generation from RES are all possible avenues to deal with the current transport environmental problems, with different vehicles such as EV and FECV having the potential to use lower- or zero-carbon energy sources.

Environment Security. Transport, while being the fastest growing sector in terms of energy use, also emits one quarter of EU greenhouse gas emissions. Carbon capture and sequestration (CCS) technologies, a process whereby CO₂ is collected from industrial exhaust streams and injected into underground storage sites, when combined with bioelectricity, have the potential for a carbon-negative environment.

Sustainable Production. The literature mining highlighted the electric energy conversion trends for future transport biofuels. However, to fully contribute to sustainable transport production, a new bio-electric energy paradigm is needed.

4.3.1. Renewable energy source

The world transport sector is going through its largest transition to new energy seen so far with the aim of:

- (a) moving away from fossil fuels;
- (b) reducing fossil fuel carbon emissions because of the harmful environmental and public health consequences;

- (c) adopting sustainable energy generation/resource management that is ecologically beneficial and healthy for present and future generations.

This global transition from finite-depletive energy to renewable energy and sustainable transport can be assisted by developments in transport biofuel/biomass, as shown in Fig. 11 (1. Energy Security). Biomass (biofuel) as a renewable energy and electricity as the energy carrier in combination with the above analysis that demonstrated that bioelectricity is better than biofuel for transportation, the potential of biofuel cells can be realized directly through the use of bioelectricity in EV and biofuel cells (also for electricity) in FECV, and indirectly through the use of hydrogen fuel cells (hydrogen gain from biomass) in FECV. The technological roadmap for future bioenergy transport is shown in Fig. 12 labeled in red font, and shows the corresponding ways to realize final electrification.

4.3.2. CCS–Negative emissions

Bioenergy combined with carbon capture and storage (BECCS) technologies can result in a permanent net removal of CO₂ from the atmosphere; i.e., negative CO₂ emissions; compared with fossil fuels and renewable energies [96–98], as shown in Fig. 11(2. Environment Security). One of the most promising options for achieving negative emissions is the production of electricity or fuels using biomass coupled with carbon capture and storage (BECCS) [99,100]. Biomass could enable CO₂ reductions not only in the electricity sector, but also in the transportation and industrial sectors for fuel, heat, and chemicals [97].

The application of carbon capture and sequestration (CCS) technologies with bioelectricity could result in carbon-negative energy sources. By sequestering the flue gas CO₂ at the power plant, the bioelectricity pathway could result in a net removal of CO₂ from the air [101,95]. Given that the transport sector has been relatively difficult to decarbonize, BECCS could be particularly valuable in reducing transport fuel carbon intensity [102,99]. On the other hand, electric transportation also provides a bridge to the use of conventional coal energy for transportation.

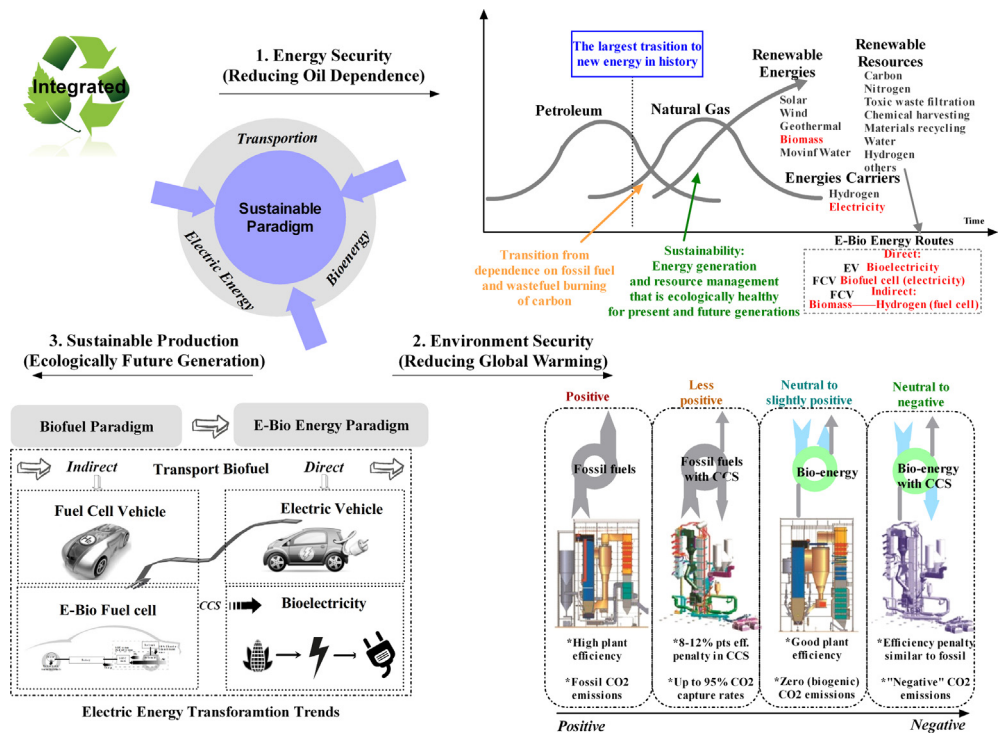


Fig. 11. Integrated sustainable paradigmatic framework.

4.3.3. Conversion framework

The literature mining analysis found that there was an existing transport biofuel paradigm which moved from traditional biofuels to advanced biofuels to biofuel cells. As the biofuels are mainly used for internal combustion engines in this paradigm, this could be named the Biofuel Paradigm. An examination of more recent literature found that there was a trend towards an electric energy conversion for transport biofuels. As shown in Fig. 11, a new bio-electric energy paradigm is expected. From the current biofuel paradigm to the new paradigm, there are both indirect and direct shifts possible.

The indirect shift may come from the further development of effective, efficient fuel cells. Current FCEV literature has been primarily focused on the hydrogen fuel cell vehicle. Biofuel cells have not yet emerged as a viable technology in the transport sector as they are still in the developmental research stage; however, the latest e-bio fuel cell

vehicle has demonstrated many advantages, and even though ethanol is being used to produce hydrogen for hydrogen fuel cells, the development indicates the progress being made in biofuel cells as the driver for fuel cell cars using the fuel's chemical energy for conversion into electrical energy.

The direct shift is in bioelectricity from the conversion of biofuel into electrical energy. This study has confirmed that compared with biofuel, the application of bioelectricity for transportation could result in higher transportation kilometers and significantly less emissions. To sum up, whether direct or indirect, the future for the transport industry lies in electrical energy being the primary transport energy.

5. Conclusions

The dependence on fossil fuels and the continuous increase in

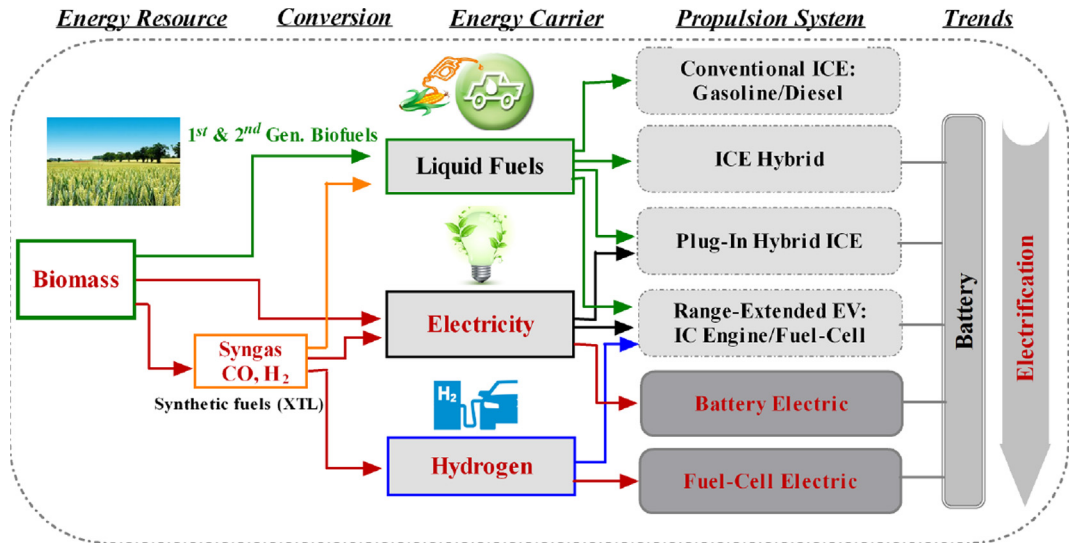


Fig. 12. Technology roadmap for future bioenergy transport.

energy use in the transport sector have focused increased attention on transport biofuels to mitigate climate change and improve energy security. While biofuels currently only contribute a small share of the energy needed in the transport sector, critical issues such as climate change, energy security, and food security all need to be considered. To ensure biofuels can play a future role in the transportation sector, this paper comprehensively examined the current state of play and the possible future directions. By combining visualization analysis with technological paradigm theory and using data-driven approaches that included science mapping and Citespace, DAS with three main modules was developed to determine the relevant research foci and identify the key areas and trends for transport biofuels. Despite significant research having been conducted, there has not yet been a paradigmatic framework for transport biofuel development. Using the DAS keyword clusters and timeline (timezone) visualizations, the focus trends were identified to allow for a comprehensive assessment of three distinct transport biofuel stages, which were in accordance with technological paradigm theory.

After combining paradigm theory with the transport biofuel development research findings, a transport biofuel technological paradigm (TBTP) was proposed, which included; a pre-shift phase (including TBTP competition and TBTP diffusion) and a shift phase (TBTP shift), which respectively identified conventional biofuels, advanced biofuels, and biofuel cells. As this paradigmatic framework gave a view of the current developments in transport biofuels, it can be regarded as a biofuel paradigm. However, from the biofuel cell emergence in the shift phase and the further DAS trend analysis, further electric energy trends were discovered, from which indirect and direct methods were revealed to give assistance to this electric energy conversion; the e-bio fuel cell vehicle for FCEV and the use of bioelectricity for EV. FCEV and EV are two potential currently available alternative vehicles to internal combustion vehicles. However, the energy source remains a hurdle, the conversions for which may be the impetus for a paradigm shift. Therefore, a bio-electric energy framework was proposed as a conversion approach for a paradigm shift from the biofuel paradigm to a bio-electric energy paradigm, which has the potential to play a significant role in a low-carbon, sustainable future.

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